Whole-spacecraft vibration isolation on small launch vehicles

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ABSTRACT

Small launch vehicles historically provide a very rough ride to spacecraft during launch. This is particularly true of solid-fueled launch vehicles. In order for the spacecraft to survive such a trip to orbit, one of two choices must be made: (1) design all structure, payloads, and systems on the spacecraft to be strong enough to survive the high launch loads, or (2) reduce the magnitude of the high launch loads. The former is not a good choice because it typically requires additional cost, schedule, and weight. The latter is the preferred choice because it allows the focus of the spacecraft design to be primarily for on-orbit performance rather that for launch survival.

Under a number of contracts from the Air Force Research Laboratory, Space Vehicles Directorate, whole-spacecraft vibration isolation systems have been in development since 1993. This work has resulted in two whole-spacecraft isolation systems (SoftRide) that have been flown on Taurus launch vehicles, the first in February 1998 with the GFO spacecraft and the second in October 1998 with the STEX spacecraft. Both of these isolation systems were designed primarily to reduce axial dynamic responses on the spacecraft due to resonant burn excitations from the motors of the solid-fueled booster. Full coupled-loads analyses were used to predict the performance of the SoftRide systems. Using the isolation requirements derived from these analyses, hardware having the correct damping and stiffness was designed to implement the isolation system. All isolation system components were extensively tested and characterized. Typical results show 85% attenuation (i.e., only 15% of original) for the worst case resonant burn condition and 59% attenuation for a combination of static plus worst case resonant burn condition in the axial spacecraft c.g. location. No detrimental effects from the SoftRide system were observed. Limited flight data from the two flights agree with the predictions. SoftRide systems are now under development for the first and second OSP launches and for the Taurus/MTI launch. Additionally, isolation systems are being designed for larger liquid-fueled launch vehicles. This isolation system technology will greatly further the goal of better, faster, cheaper, and lighter spacecraft.

Keywords: launch, vibration, isolation, attenuation, spacecraft, launch vehicles, launch environment

1. INTRODUCTION

Launch dynamics are a major design driver in structural design of spacecraft. Launch survival is often a more difficult design problem than is ensuring operational performance in orbit. Either the dynamic launch loads on the spacecraft must be reduced or the spacecraft structure must be stiffened. Stiffening the structure adds weight, but reducing the dynamic loads on the spacecraft by whole-spacecraft vibration isolation could allow lighter weight systems. Reduction of the launch loads would greatly reduce the risk that the spacecraft and its instruments will be damaged from vibration during their ascent into orbit, and would also allow more sensitive equipment to be included in missions. As the severe launch environment also accounts for much of the expense of designing, qualifying, and testing spacecraft components, significant cost can also be saved if loads are reduced.

Other auxiliary approaches exist such as passive damping or local isolation of specific components. While often effective, these are spacecraft-specific and invariably add to the time and cost of development. The relentless search for better, faster, and cheaper spacecraft mandates the pursuit of technology such as whole-spacecraft vibration isolation that can potentially streamline both design and qualification for a wide range of new spacecraft.

No one would consider driving a vehicle over a rough road where the passenger cabin was hard-mounted to the wheels. A good isolation system under the passenger cabin is mandatory. Spacecraft, on the other hand, are normally hard-mounted to the top of the launch vehicle (LV). The concept of vibration isolating the complete spacecraft from the launch vehicle has been desired for years. A whole-spacecraft vibration isolation system is more than tuning the stiffness of a payload adapter

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for a spacecraft to produce a mechanical filter for certain load events. Whole-spacecraft vibration isolation produces a substantial change in the dynamic properties of the combined system and is bound to have side effects that must be addressed. Flight acceptance can occur only when both the LV and spacecraft contractors are satisfied that no unacceptable events will occur.

Under a number of contracts from the Air Force Research Laboratory, Space Vehicles Directorate, CSA Engineering has been working on the concept of whole-spacecraft vibration isolation systems (hereinafter referred as the SoftRide system) since 1993. A number of design and performance analyses were performed on a variety of liquid-fueled and solid-fueled launch vehicles, all of which showed great promise. However, it was not until the launch of the GFO spacecraft on Orbital Science's Taurus launch vehicle in February 1998 did an isolation system designed to vibration-isolate the complete spacecraft actually fly. Since that time, a second system has flown, systems are under hardware design for three upcoming flights, and design work has been performed on several additional launch vehicle/spacecraft combinations.

Typical vibration isolation systems work by connecting the isolated structure (payload) to the base structure (launch vehicle) by means of a resilient mount or mounts. The resilient mounts have low relative stiffness as compared to the base and payload, and some degree of structural damping. The stiffness of the resilient mounts is tuned so that the frequency of vibration of the supported payload on the resilient mounts is a specified value (isolation frequency). Damping in the resilient mounts reduces the amplitude of response of the payload at the isolation frequency when the system is under external excitation. The resilient mounts must allow relative motion between the vibrating base structure and the payload at the isolation frequency, which is referred to as the isolator stroke.

Because the spacecraft is a major structural component of the launch vehicle/spacecraft dynamic system, variations in the isolation frequencies greatly effect the dynamics of the launch vehicle/spacecraft system. Any unpredicted changes in the dynamics could have an adverse effect on the control system of the launch vehicle and cause instability and thereby loss of the mission. Therefore, the stiffness properties of the isolation system must be relatively constant for the duration of the flight. This requires a linear isolation system under all load cases, including preloads from –2g's to +6g's accelerations of the launch vehicle. This eliminates using an elastomeric material (i.e., rubber mounts) as the stiffness component of the isolation system. Owners of spacecraft, which costs tens to hundreds of millions of dollars, demand a metallic connection between the spacecraft and the launch vehicle. This connection, which is the SoftRide system, must also provide a fail-safe connection, must be able to handle, without overstressing, the deflections due to the sum of the dynamic and quasi-static acceleration loads of the spacecraft, and must be of minimal height (reduces payload volume) and weight (reduces payload weight).

On expendable launch vehicles, spacecraft are attached to the launch vehicle at their base either at discrete points or by a band clamp. If the attachment stiffness is made soft in the axial or thrust axis, then we refer to that type of isolation system as an axial system. Axial systems can provide isolation in the axial and two rocking directions and therefore can isolate against both axial and bending modes of the launch vehicle. If the attachment stiffness is made soft in the in-plane directions at the attachment points, then that type of isolation system will be referred to as a lateral or shear isolator. Whole-spacecraft vibration isolation systems may also be a combination of these.

This paper discusses axial SoftRide systems designed for and flown on small, solid-fueled launch vehicles. Even though these systems were designed to reduce transient vibration loads below 80 Hz, they performed extremely well at reducing high-frequency loads. This high-frequency attenuation is discussed as it pertains to structure-borne acoustic and shock loads on the spacecraft.

2. ISOLATION DESIGN METHODOLOGY

The SoftRide vibration isolation systems seek to reduce dynamic loads on a payload by blocking the transmission of dynamic loads present in a base structure to which the payload is attached. The design of classical vibration isolation systems typically assumes that the base is rigid and the isolated payload has dynamics only well above the isolation frequency. Contrary to this, the design of a SoftRide system must be done with full knowledge that the structures on either side of the isolation system, namely the launch vehicle and the spacecraft, are both very rich in dynamics. This necessitates that the SoftRide system must be approached from the perspective of system-level dynamics.

Some of the typical design constraints are weight, volume, and strength. Two other major constraints on the design of the isolation systems are:

- Do not introduce excessive spacecraft to fairing relative displacement.
- Do not introduce modes that are too low in frequency or high in amplitude such that they interfere with the LV attitude control system.

The design of the isolation system therefore requires coupled-loads analysis (CLA), along with detailed design analysis. The basic procedure (Figure 1) involves the following steps:

- Preliminary CLA with worst load cases to optimize system-level isolator performance and get component-level requirements
- Isolator concept design to meet component-level performance requirements
- Isolator loads analysis to determine design loads for isolator strength design
- Isolator detailed design to arrive at a design that meets all strength and performance requirements
- Complete CLA using final detailed isolator models in the system model to verify system-level performance

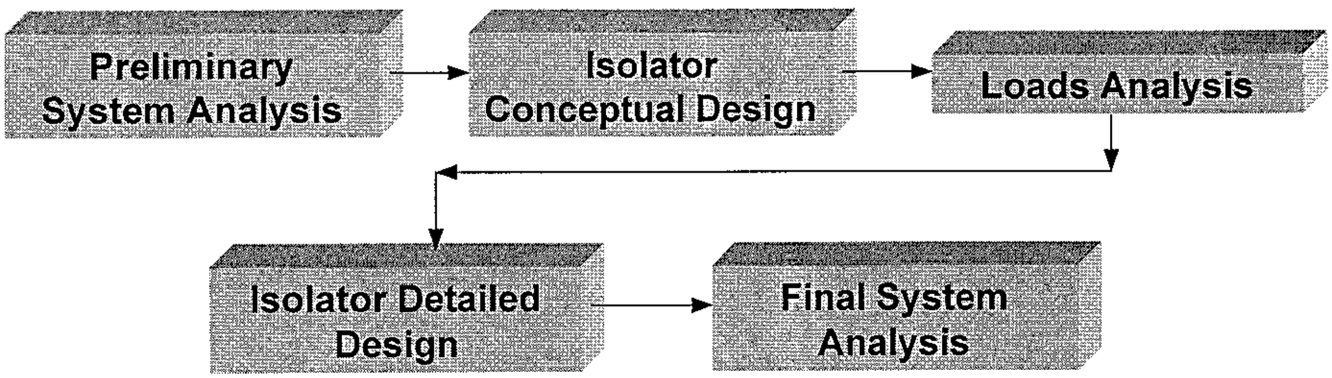

Figure 1 SoftRide design methodology

The CLA must be performed with actual launch vehicle and spacecraft models. The typical procedure at CSA is to obtain LV models and loads for worst case conditions from the LV manufacturer and perform CLA with the latest model of the spacecraft supplied by its manufacturer. Once the detailed isolator design analysis is completed, then a model of the isolators is delivered to the LV manufacturer for a complete and final CLA.

3. AXIAL VIBRATION ISOLATION

3.1 Background

Dynamic launch loads from some launch vehicles, particularly solid boosters, may be drastically attenuated through the use of an axial (longitudinal, thrust direction) SoftRide isolation system. A common axial dynamic load event, referred to as resonant burn, occurs in solid-fueled boosters like the Castor 120 and the PeaceKeeper. This event causes large dynamic loads on the spacecraft in the 45-60 Hz range and is primarily an axial load event. SoftRide systems have been designed, built, and flown on two flights on Orbital Science Corporation's Taurus launch vehicle, and hardware has been or is being designed for several other flights, including flights on an additional Taurus, Athena, and Orbital-Suborbital Program (OSP) launch vehicles.

The resonant burn load case on the Taurus LV caused unacceptably low margins on the GFO and STEX missions. The Air Force Research Laboratory and CSA were contacted about the SoftRide system within five months of the scheduled launch of each mission. Preliminary analyses performed within ten days of each contact predicted that an axial-type of SoftRide system would reduce the dynamic loads on the spacecraft to acceptable levels.

The specific objectives and constraints for the isolation system were:

- Reduce dynamic loads imparted from the launch vehicle to the spacecraft due to the resonant burn load case. This was the most severe load case for the spacecraft.
- Reduce dynamic loads imparted from the other load cases, if possible.
- Do not change any existing flight hardware

- Insert the isolation system into a field joint
- Deliver tested flight hardware within four months

For both the GFO and STEX flights on Taurus, the isolation design was very similar, so only details of the GFO design are discussed here. Flight data and attenuation for both missions will be discussed in a later section.

Design of the SoftRide System for GFO

For the GFO mission, CSA obtained finite element models and loads of the Taurus launch vehicle and the GFO spacecraft from Orbital Sciences Corporation (Orbital) and Ball Aerospace and performed coupled loads analyses. These analyses started with a uniquely simple isolation concept that fits into an existing field joint, requires very little volume, is lightweight, and does not require any modifications to existing flight hardware. Preliminary analyses were used to size the stiffness of the isolation system for load-reducing performance. Then, maximum loads from Orbital's full coupled loads analyses were used to finalize the isolator design for strength, endurance, manufacturability, etc.

Coupled loads analysis showed that the isolation system significantly reduced spacecraft responses due to the resonant burn load. For example, the spacecraft net C.G. response in the axial direction was reduced by a factor of seven by using the isolation system (Figure 2).

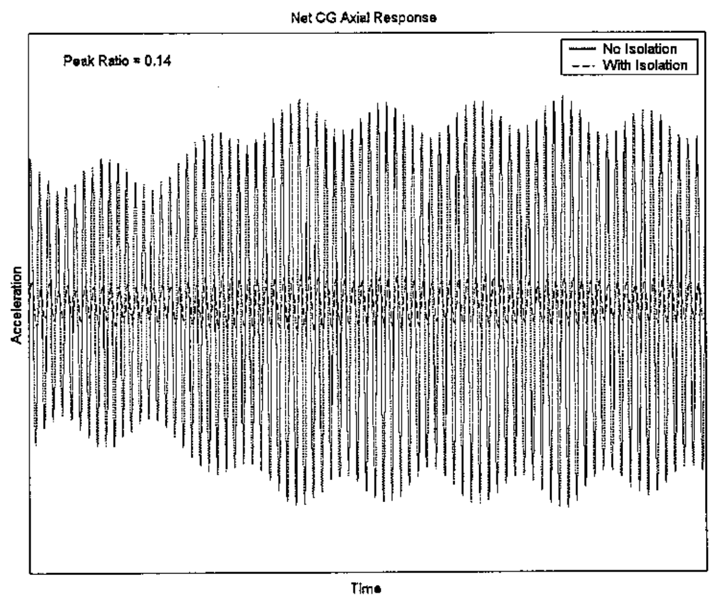

Figure 2 Spacecraft axial C.G. response, resonant burn load

A hardware concept was developed and flown on the GFO/Taurus mission. Due to the proprietary nature of the system (patent pending), the concept will not be shown herein. This whole-spacecraft isolation system was made up of a series of isolator elements. The system had the following attributes:

- Provided extreme reductions in most spacecraft responses to the resonant burn load
- Met all design constraints
- Low weight =21 lb (spacecraft weight = 800 lb)
- Small size (spacecraft moved forward <1 inch)
- Mounted to existing LV field joint
- Did not require any changes to existing flight hardware
- No linkages, fluids, or nonlinearities

3.2 Component and System Testing

Extensive component-level and system-level testing was performed on the GFO/Taurus SoftRide isolation system. These tests were done for the purposes of qualification and acceptance of the isolation system for flight. Component-level tests included:

- Thermal cycling
- Sine sweep
- Complex stiffness
- Random endurance
- Sine endurance

The measured stiffness and damping of an isolator element at various temperatures is shown in Figure 3. The use of viscoelastic material causes both the stiffness and the damping to be frequency dependent. These measured values matched analytical predictions within 2%, indicating that the model of the isolation system was very accurate.

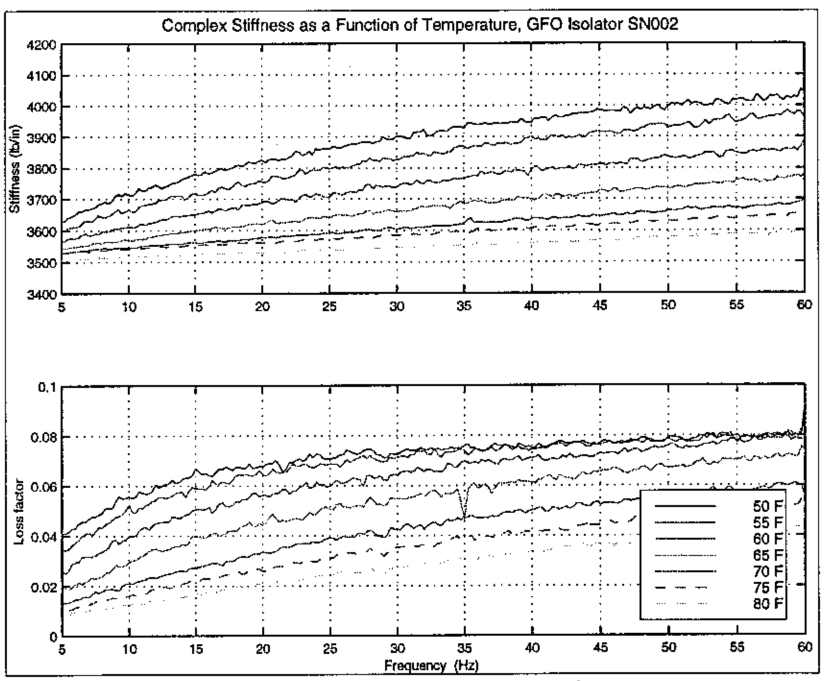

Figure 3 Complex stiffness measurements at various temperatures

The isolation system was made up of a series of identical isolator elements. The consistency of these elements (flight plus spares) is illustrated by the stiffness and damping measurements shown in Figure 4.

The isolation system was tested for its ability to withstand shock inputs. The results of these tests are discussed in a later section.

System-level tests were performed using the flight isolators, other flight hardware, and a mass simulator for the spacecraft. The system assembly was placed on a large shake table and several sine sweep, random, and modal tests were performed, both with and without the isolation system. The results showed that the isolation system performed exactly as predicted analytically. Figure 5 shows an overplot of the analytical and test PSD response at the top of the mass simulator in the longitudinal direction due to a random base input. These system tests indicated that the isolation system would perform as intended, reducing dynamic loads on the spacecraft.

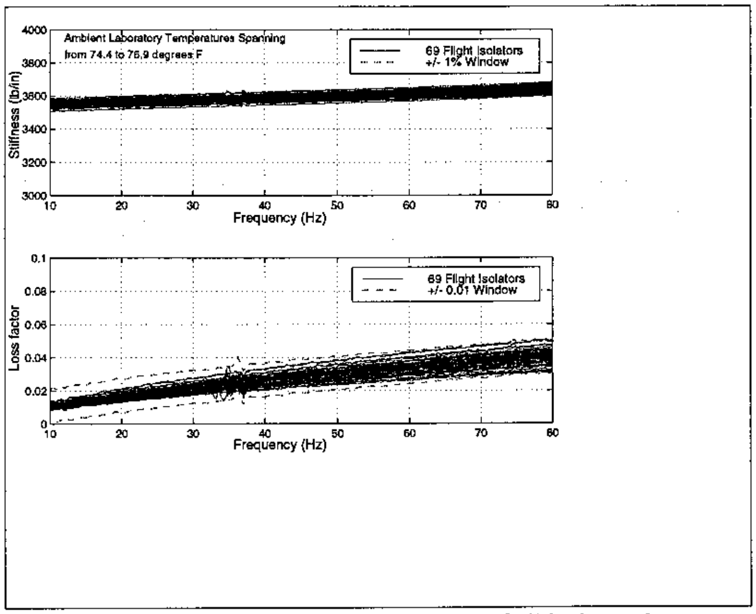

Figure 4 Complex stiffness measurements of all isolator elements

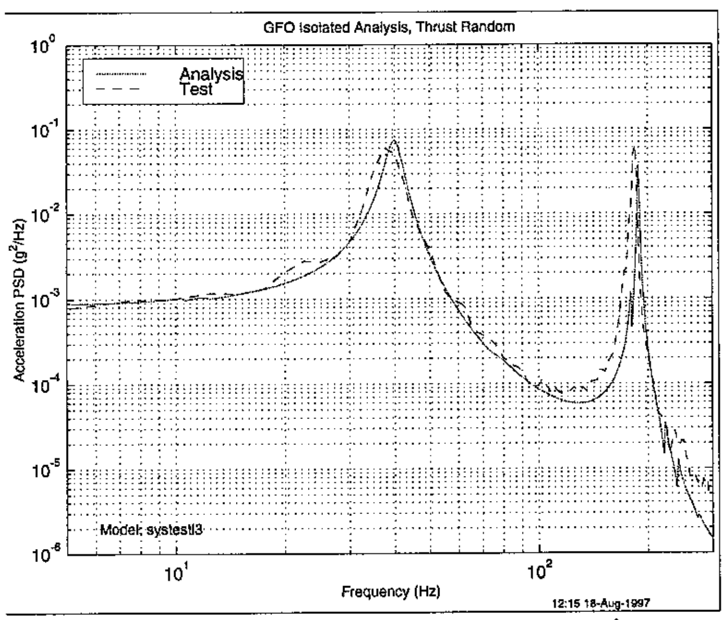

Figure 5 System test and analysis response comparison

4. BROADBAND ATTENUATION

SoftRide whole-spacecraft vibration isolation systems have been designed, fabricated, tested, and flown for the explicit purpose of attenuating transient dynamic launch vibrations (<80 Hz). To date, two SoftRide systems have been flown on Orbital's Taurus launch vehicles, the first in February 1998 with the GFO spacecraft and the second in October 1998 with the STEX spacecraft. Both of these isolation systems were designed primarily to reduce axial dynamic responses on the spacecraft due to resonant burn excitations from the motors of the solid-fueled booster. A review of flight data from the GFO and STEX flights has shown significant reduction not only in transient vibration but also in random vibration and shock. The following is a presentation of the flight data pertaining to the performance of the SoftRide systems for both flights, with discussion focused on the high-frequency content.

4.1 SoftRide Flight Data - Taurus/GFO Mission

The GFO spacecraft interface was instrumented with six accelerometers that measured axial and lateral vibration during the flight. A single accelerometer was mounted in the flight direction just forward or on the soft side of the isolation system. The remaining spacecraft interface accelerometers were mounted aft or on the hard side of the isolation system. The accelerometers were sampled at 4000 samples per second with 8 bit resolution. Variable capacitance accelerometers were used which measured both the steady state and transient acceleration.

An overplot of the time history of the response, during the first stage burn, from accelerometers mounted on the hard side (below isolators) and soft side (above isolators) of the isolation system is shown in Figure 6. The reduction due to the spacecraft isolation system is readily apparent by comparing the two time histories. The isolation system significantly reduces the vibration level to the payload by 50% for all load events.

It is of great interest to examine the performance of the SoftRide isolation system in the frequency domain. This allows inspection of the broadband attenuation characteristics of the SoftRide system. The dynamic system made up of the launch vehicle and spacecraft is non-stationary due to continual propellant depletion and stage separations. Also, the highly transient nature of most launch load events precludes digital signal processing of the flight data averaged over the entire launch window. Therefore, the frequency content of the transient flight data is best observed by creating waterfall PSD plots. These plots show the PSDs of 2-second windows of transient data, overlapped by 1 second, and stacked up next to each other.

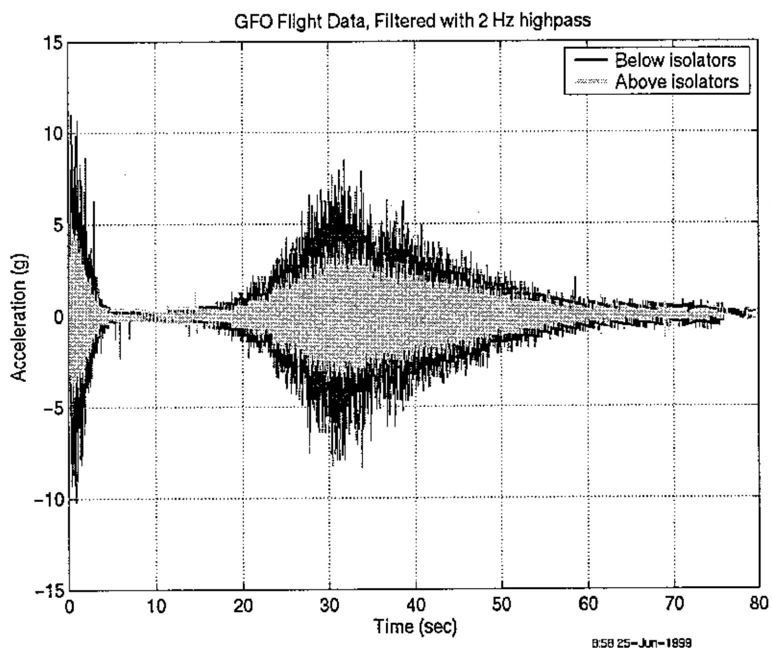

Figure 6 GFO flight data – below and above isolators

Figure 7 shows the waterfall plot for the axial acceleration below the isolators from the GFO flight. Similarly, Figure 8 shows the axial acceleration above the isolators from the GFO flight. Note that the sample rate of 4000 Hz only allows data to be examined up to 2000 Hz. Examination of these plots shows that the SoftRide system provided significant reductions in the acceleration levels across the broadband spectrum. It is believed that for this data, which was acquired during first-stage burn, the high frequency content (800 Hz to 1500 Hz) is caused by structure-borne acoustic energy.

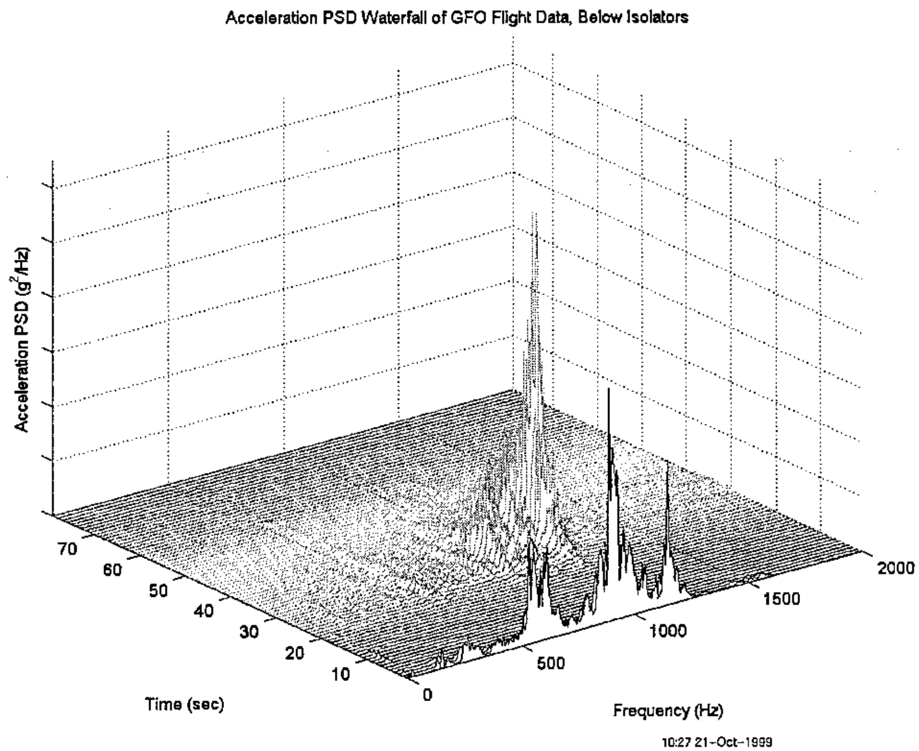

Figure 7 Waterfall PSD of GFO data - below isolators

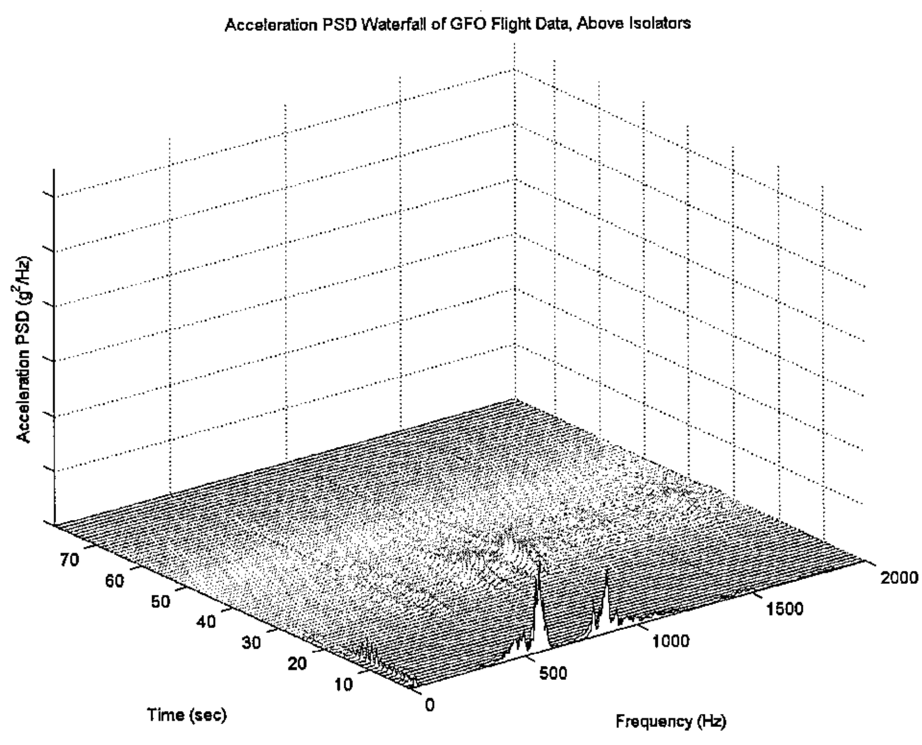

Figure 8 Waterfall PSD of GFO data - above isolators

4.2 SoftRide Flight Data - Taurus/STEX Mission

The Taurus/STEX SoftRide isolation system was very similar to that of GFO but "tuned" for this mission. The STEX spacecraft was heavier than the GFO and therefore the isolation system was larger. With one successful flight of this system, the program offices allowed a slightly more aggressive design (lower in frequency) to be flown. Finite element models of the LV and spacecraft were obtained and full coupled-loads analyses were performed to design the isolation system. All of the same types of tests that were performed on the Taurus/GFO isolation system were performed on the Taurus/STEX system with the exception of a system test.

For the Taurus/STEX mission, data from two accelerometers, again one below and one above the isolators, was obtained. An overplot of this data is shown in Figure 9 (this data has been high-pass filtered to eliminate the quasi-static accelerations). This data shows a factor of five reduction in the broadband acceleration levels above the isolators.

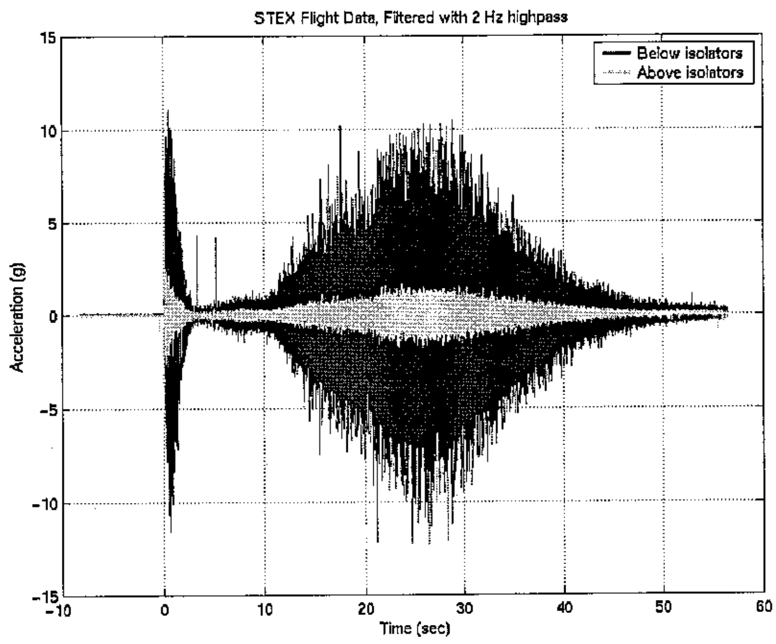

Figure 9 STEX flight data - below and above isolators

A PSD of this data, averaged over the entire transient record, is shown in Figure 10. While this type of averaging is not strictly correct due to the transient nature of the data, it does shed some light on the broadband attenuation. The spike at approximately 21 Hz is a lift-off event that briefly excites the first axial mode of the vehicle. The resonant burn condition occurs around 50 Hz. This data shows the reductions obtained at the higher frequencies due to the SoftRide system. Waterfall PSD plots of this data are shown in Figure 11 and Figure 12. The high frequency accelerations below the isolators (Figure 11) may be due to structural-borne acoustic energy. The SoftRide system has greatly reduced the structural-borne acoustic vibration on the spacecraft (Figure 12).

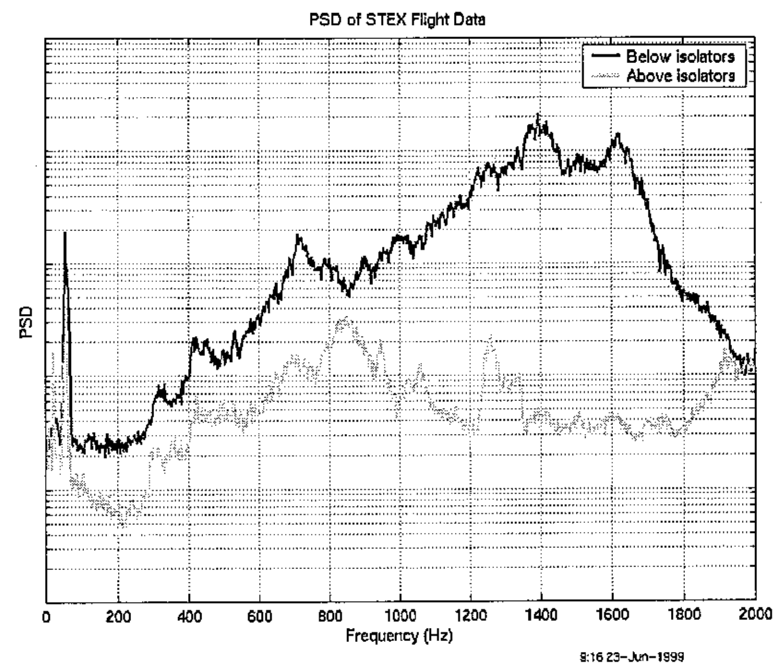

Figure 10 PSD of Taurus/STEX flight data

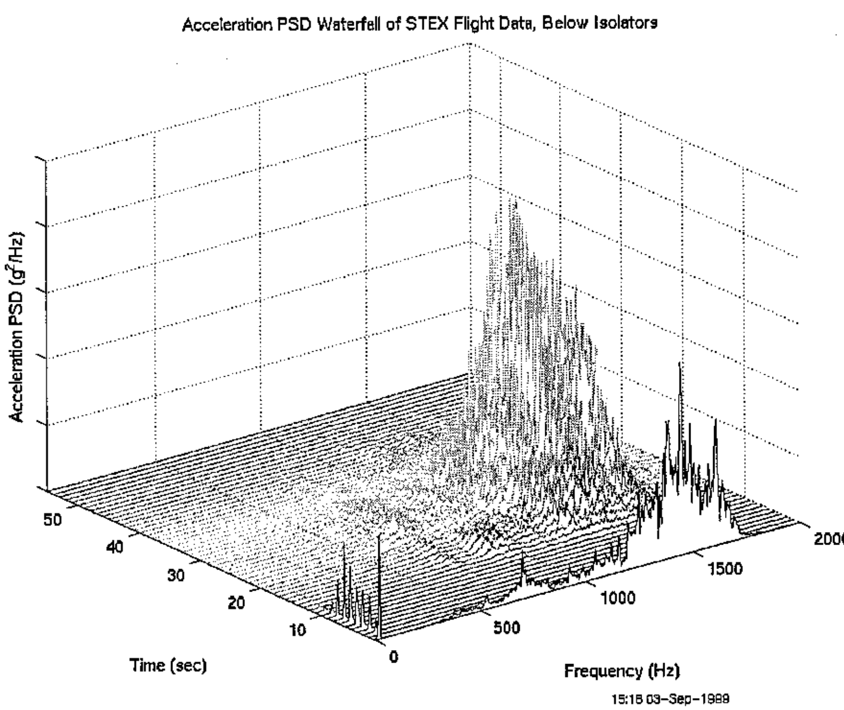

Figure 11 Waterfall PSD of STEX data - below isolators

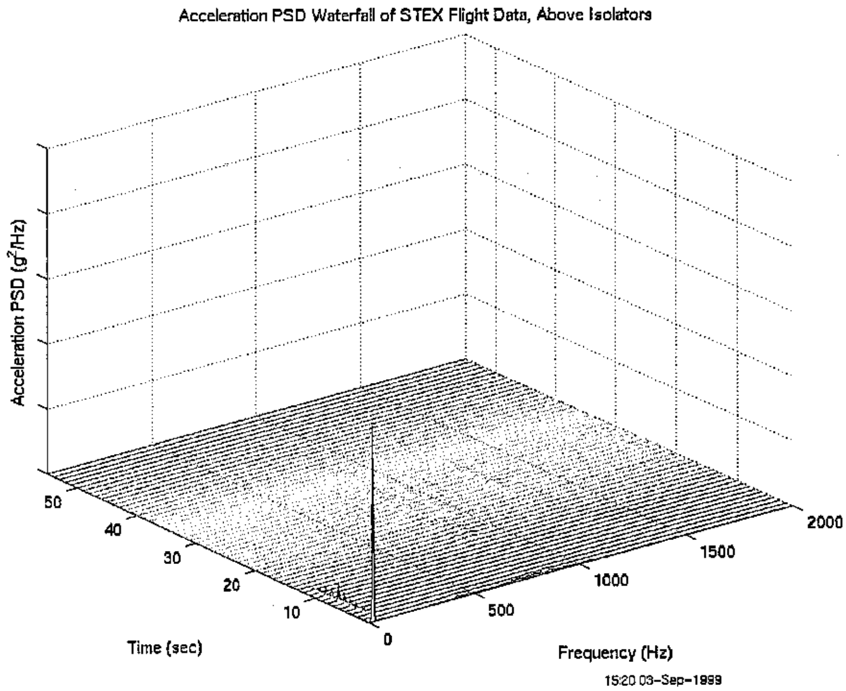

Figure 12 Waterfall PSD of STEX data - above isolators

4.3 Attenuation of Shock

The GFO SoftRide isolation system was tested, at the component level, for its ability to withstand shock inputs. A shock simulating a flight event such as a stage or fairing separation was input to the base of the SoftRide system and the isolated response was measured. The results of these tests showed that not only did the system survive the largest shock input, but also it gave excellent shock attenuation above 100 Hz (see Figure 13 and Figure 14). Therefore, this isolation system reduced loads on the spacecraft that were due to shock from stage and fairing separations.

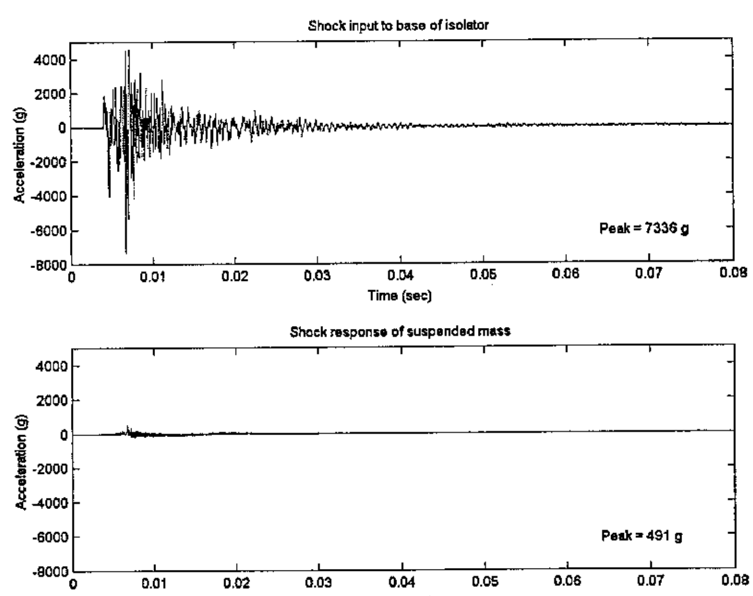

Figure 13 Isolator shock test data

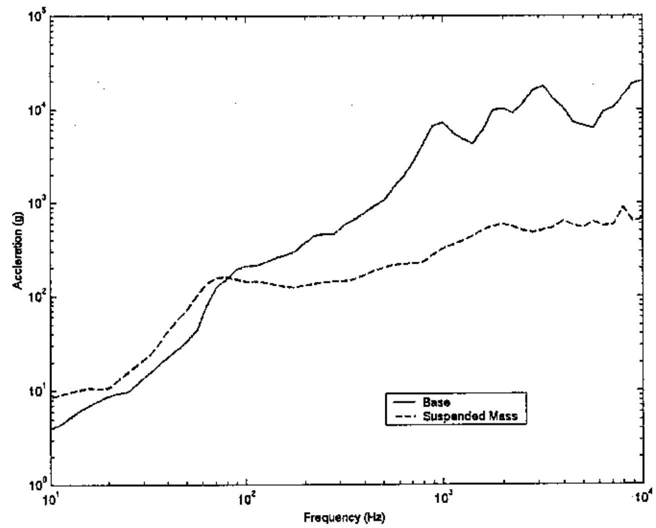

Figure 14 Frequency content of shock data

5. CONCLUSIONS

There is a need to reduce launch loads on spacecraft so that spacecraft and their instruments can be designed with more concentration on orbital performance rather than launch survival. A softer ride to orbit will allow more sensitive equipment to be included in missions, reduce risk of equipment or component failure, and possibly allow the mass of the spacecraft bus to be reduced. These benefits apply to military as well as commercial spacecraft.

The SoftRide whole-spacecraft vibration isolation systems for both the Taurus/GFO and Taurus/STEX missions proved to be a very effective means of reducing spacecraft responses due to the broadband structure-born launch environment. From both the transient data and the waterfall PSDs, it is clear that the SoftRide whole-spacecraft vibration isolation system performed very well to reduce structure-borne vibration levels transmitted to the spacecraft. The isolation system was designed specifically to reduce the effects of solid motor resonant burn in the 45 Hz to 60 Hz frequency range, which it did very well. It should also be noted that the SoftRide vibration isolation system provided extreme reductions of shock and structure-borne acoustics at higher-frequencies.

The isolation system hardware design was elegant in its simplicity, which ultimately played a great part in its acceptance by both the spacecraft and launch vehicle manufacturers. This isolation system was simply inserted at an existing field joint. No flight hardware changes were required. The only change was to the guidance and control algorithms to account for bending frequency changes introduced by the isolation system.

In the end, the choice to fly the isolation system proved to be a tremendous risk-reduction for the spacecraft by drastically increasing the spacecraft margins. Because of the success of these flights, this isolation system design is being used on several upcoming flights.

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